Lead-Acid Battery:

Techniques for Bonding the Positive Plates

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Two fusion-bonding processes have been devised for bonding adjacent curved- or flat-lead lugs of the positive plates used in the new Bell Laboratories lead-acid battery. We describe both processes, but emphasize the Mechanical Thermal Pulse (MTP) Continuous Fusion-Bonding Process, which was chosen for use in the prototype battery manufacture. This process is capable of bonding many battery lugs simultaneously with simple equipment and with relatively precise control of bonding parameters.

I. INTRODUCTION

The purpose of this article is to discuss the bonding of the positive plates of the new lead-acid battery to form a complete battery cell. The negative plates are bonded by a center-pour technique described elsewhere in this issue.

Figure 1 shows part of one element of tbe new battery, using an early prototype positive-plate design. During assembly, negative plates are stacked between positive plates until the element is complete; typically ten or more negatives are used. Eacb circular positive plate bas four or more pure-lead lugs. These must be bonded to tbe corresponding lugs on the adjacent positive plates.

At the bottom of Fig. 1 are two unpasted positive plates after bonding with a pasted negative plate in position. Note that the battery lugs in tbis early design were flat to facilitate bonding studies. Figure 2 shows a pair of lugs cut out of tbe battery plates. This is a later design using curved lugs, approximately 0.188 inch thick and 2.25 incbes long and formed out of pure lead. It is desirable to use curved lugs to provide a maximum cross section of the lug, maximum electrical conductance, and simplest overall geometry.

Two new concepts of fusion bonding were developed. Botb are to be

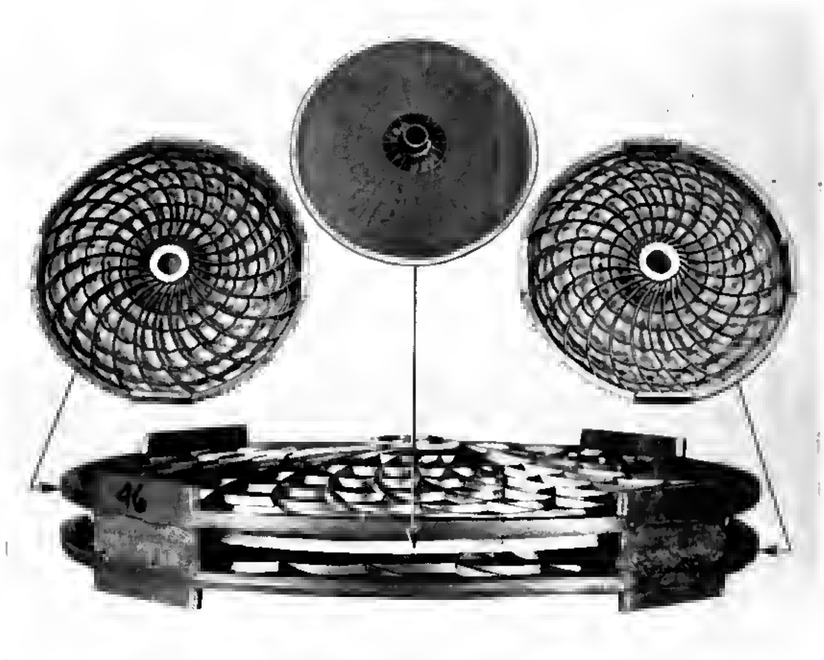


Fig. 1—Exploded and assembly view of three battery plates.

used in manufacture, one for bonding the positive plates and the other for a secondary bonding operation. This article, therefore, considers both processes and discusses bonding of both flat and curved lugs.

II. BONDING REQUIREMENT

The left-hand sketch in Fig. 3 represents a cutaway view of a bond area. Appropriate spacers and insulators are normally interspersed between the negative and positive plates. Note that there is complete access to the outside of the positive-plate lugs in the bond area but extremely limited access to the inside bond area.

A fundamental requirement is that each pair of lugs must be bonded completely without voids or cracks. This requirement is necessitated by the stresses occurring in the lead as a battery is floated. Accelerated life tests have confirmed that the cracks in the bond region tend to widen and deepen, increasing the internal battery resistance. This results in degradation of performance and can eventually progress sufficiently to cause failure.

The first prototype batteries were assembled and bonded with a hand Heliarc welding technique and with the plate axis vertical. This was relatively laborious and time-consuming witb typical bonds requiring up to a minute or even more. In addition, considerable difficulty was experienced in achieving crack-free, complete penetration of tbe lugs.

It was recognized that for faster bonding (*i*) it would be necessary to determine whether a confining, sealing mold could be applied to tbe present battery geometry to afford reliable containment of the molten lead, and (*ii*) the battery axis should be in a horizontal position so tbat gravity would help control the molten lead during bonding. An alternate approach would be to attempt to bond the battery plates witbout the use of any confining, sealing mold or back-up fixture. It will be sbown that both approaches were proven feasible but the latter approach proved to be more advantageous.

Several other points in tbe battery design influenced the choice and design of the bonding method. Due to the unusually long life expectancy for this battery design, contamination of the bond area had to be kept

Fig. 2—Two positive plate lugs.

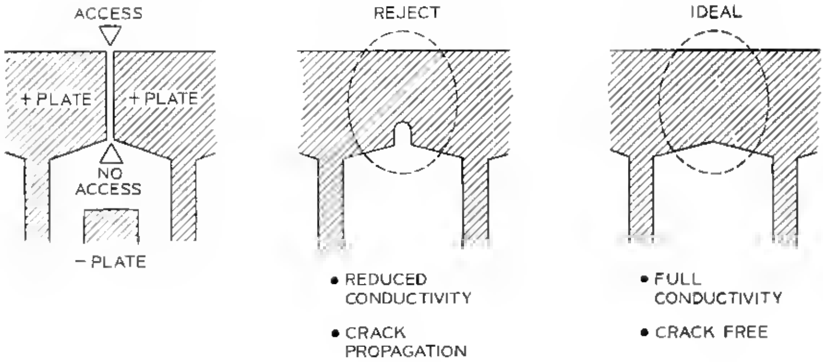


Fig. 3—Positive plate bonding.

to a minimum. In addition, both the magnitude and duration of the peak temperature in the bond area had to be kept to minimum values to prevent thermal damage to the pasted area of the plates, the separators or the insulators.

III. BONDING METHODS

Groups within the Bell System investigated several different bonding methods. The processes included: Heliarc welding, infrared bonding, laser bonding and mechanical thermal pulse or MTP bonding. Table I compares bonding process characteristics. Note that the target temperature, the melting point of pure lead, is approximately 327°C. It can be seen that the MTP processes have the lowest peak temperatures, yet they possess very high heating rates. This has proven useful in minimizing variations in bond temperature. In general, with a given work part and its typical variation in characteristics, the higher the ratio of the effective source temperature to the target temperature of the work part, the more crucial automatic temperature control becomes. In this application, conventional feedback techniques for controlling were not adequate, so a new approach was developed.

Figure 4 illustrates the general MTP principles involved. Thermal energy is stored in an appropriately shaped metal block or ram. This thermal energy is transferred by thermal conduction to the two or more work parts to be bonded. Sufficient pressure is applied between the hot ram and the work parts to assure low thermal resistance values at the interface, making it possible to transfer rapidly relatively large quantities of thermal energy. The transfer is relatively independent of variations

in the characteristics of the work parts. Note that the peak temperature of the ram, and thus of the work parts in the bond area, has a precise, predetermined upper limit—that is, the control temperature of the ram itself. The ram can either be pulse or continuously heated to the desired temperature.

Typical variables in work parts tend to have a strong effect on the thermal energy transferred, but the effect is only minor in the MTP processes. Such variables include emissivity, reflectivity, color, surface roughness, electrical conductivity, volume thermal conductivity, and surface contamination.

IV. MTP HEATED RAM PROCESSES

The MTP fusion-bonding process that makes use of a heated ram is extremely simple in concept. Figure 5 illustrates the basic principles. A carefully shaped, relatively large ram of a material with high thermal conductivity and with high heat capacity, such as copper, is preheated

TABLE I—COMPARISON OF BONDING PROCESSES

Process	Effective Source Temperature	Energy Transfer Method	Energy Transfer Magnitude	Temperature Control Method
Mechanical Thermal Pulse (MTP)	800°C*	Conduction	Heated ram transfers fixed amount of energy	Determined by ram or tip temperature
Radiant (Incandescent)	3400°C	Radiation	Feedback varies energy transfer rate or duration	Determined by total energy transferred
Radiant (Arc)	5700°C	Radiation		
Oxy-Acetylene	3200°C	Forced convection		
Heliarc	5700°C	Joule heating plus ion bombardment		
Atomic hydrogen arc	10,000°C	Joule heating plus ion bombardment		
Laser	$\sim 10^{8}$†	Radiation		

* Maximum ram or tip temperature.
† Based on solving the Stefan-Boltzmann equation.

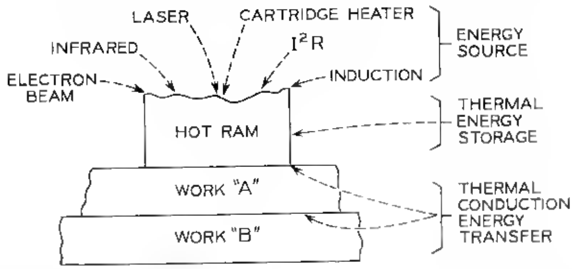


Fig. 4—Principles of processes of bonding with the mechanical thermal pulse (MTP) method.

to a specified temperature. The ram is positioned over the honding fixture and then plunged with a low force against the two lugs to be bonded contained in a confining hack-up fixture.

The thermal conductivity of copper is approximately 11 times greater than that of lead, and copper's heat capacity per unit volume is 2.35 times greater than that of lead. Consequently, the heated ram stores sufficient thermal energy to form a bond between the two lead lugs with a relatively low temperature drop and rapid recovery. Typically, bonds are formed in one to ten seconds. It is possihle to combine two or more rams to create two or more honds simultaneously.

The ram stroke is controlled so that the ram first melts the surface of the lead lugs. Then the ram progressively penetrates to the inside bottom of the lugs as melting continues. The penetration can be readily controlled so that the ram either penetrates completely to the inside bottom of the lug, or to within a predetermined distance from the back of the lug. Consequently, the heated ram offers positive assurance that the thermal energy completely penetrates the entire cross section of the lug.

It is appropriate at this point to compare the MTP heated ram process with alternative honding techniques. During hond formation between the two lead lugs, the solid, room-temperaturc lead is heated to temperatures beyond its fusion temperature and changes from a solid to a liquid. Consequently, the electrical, thermal, optical, mechanical and metallurgical characteristics of the lead change appreciahly throughout the formation of the hond. Specifically, changes may occur in electrical resistance, emissivity, density, thermal conductivity, ductility, and so on. These changes in characteristics must he taken into account and appropriately compensated for if accurate temperature control is to be maintained. Since the MTP heated ram completely penetrates the lead

lugs, transfer of the thermal energy to the work parts depends primarily upon the relatively unchanging thermal characteristics of the heated ram itself. In addition, since the ram material has a relatively high thermal conductivity, the ram penetration through the center of the bond area assures a minimum temperature differential between the outer and inner surfaces of the bond area.

The shape of the ram is chosen to provide a storage space for the molten lead that is displaced by the volume of the beated ram. Tests have confirmed that this molten lead can be stored in a hollowed-out center section of the ram. After the initial surface melting, the ram starts to penetrate the two lugs, forcing the displaced molten lead into the hollow center. Very little lead, if any, flows outside the confines of the ram itself. As the ram is removed, the molten lead flows back into place to form the bond. The copper ram is plated with approximately one mil of nickel to protect against oxidation and minor abrasion.

Lead oxidizes quite readily and the oxide is an excellent thermal insulator, even in relatively thin layers. Initially, tbe oxide coating adheres poorly to the surface of the ram. Consequently, with this method it is desirable to wipe the ram with a metal bristle brush after each bond or set of bonds to remove this loosely adhering coating from the ram. The ram can be rapidly and reliably cleaned by a single in-line, one-stroke motion. Appropriate gas jets, protective atmospheres or other techniques might be considered as alternative cleaning methods.

Calculations indicate that from 1000 to 5000 joules are required to bond each pair of lead lugs. The range of energy shown encompasses different bonding speeds. At the most rapid rates investigated—that is, about one second bonding time—minimum thermal energy is required. At easier-to-control, more practical bonding times of from three to seven seconds, the larger quantity of thermal energy is required since a larger

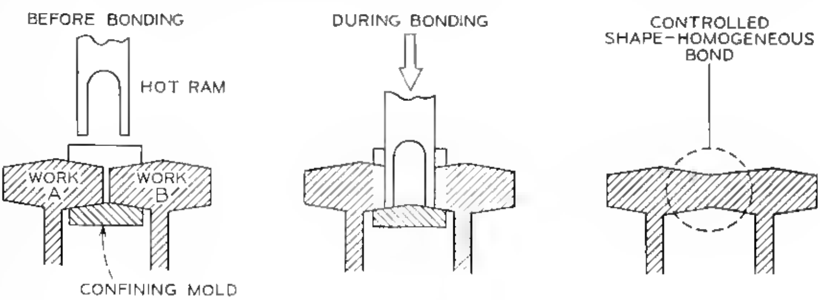


Fig. 5—Fusion bonding with an MTP heated ram.

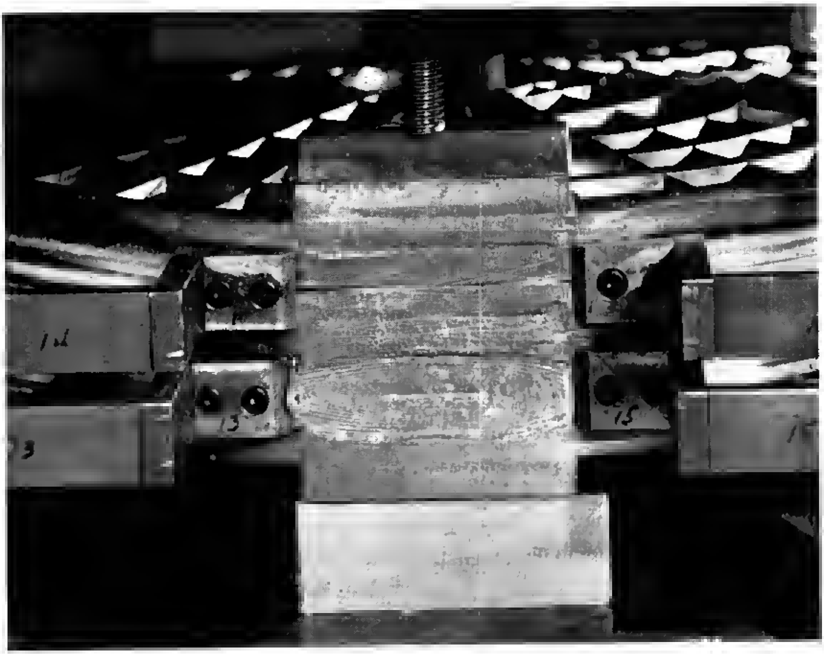


Fig. 6—Positive plate bonding fixture.

volume of the lead work parts absorhs appreciable thermal energy. The optimum time at the present stage of development is approximately five seconds.

A major advantage of the MTP heated ram fusion process is its capahility of transferring this relatively sizable quantity of thermal energy rapidly, repeatahly and with minimum variation in the peak temperature of the work parts. The MTP ram temperature is typically a maximum of 600 to 700°C; thus the lead temperature is limited to this maximum value. The relatively low temperatures used in MTP fusion processes are beneficial in reducing metallurgical changes in the lead structure, reducing turhulence and vaporization, and eliminating hoiling in the bond area.

The forces required to create these honds are surprisingly low. Typically they range from three to five pounds for a bond length of approximately 2.25 inches.

Figure 6 is a close-up view of a typical back-up fixture as viewed from the top, looking down from the ram's position. Note that two lugs have been bonded and that the adjacent two lugs are in position ready for

bonding. The fixture slides in from both sides and mates to form a containing seal against loss of the molten lead. Figure 7 shows a front and back view of a typical bond along with two metallurgical sections confirming that complete fusion bonds have indeed been achieved.

Tests were made with a chromel-alumel thermocouple bonded to the bottom area of the ram tip. Storage oscilloscope traces of the ram temperature drop during a typical bonding cycle of actual battery lugs are shown in Fig. 8. This chart confirms that the tip temperature initially dropped rapidly to approximately the melting point of lead (327°C) and then more slowly rose to approximately 455°C at the end of six seconds. The quantity of thermal energy required to melt the lead is approximately 40 percent of the energy required to raise the lead from room temperature to 455°C. Consequently, the temperature of the lead rises rapidly to its melting point, then tends to remain there until all the lead in immediate contact with the ram becomes molten. Only then does the temperature of the lead start to rise above its melting point. In addition, the relatively small differential between the temperature of the ram and the melting point of lead helps assure that the molten

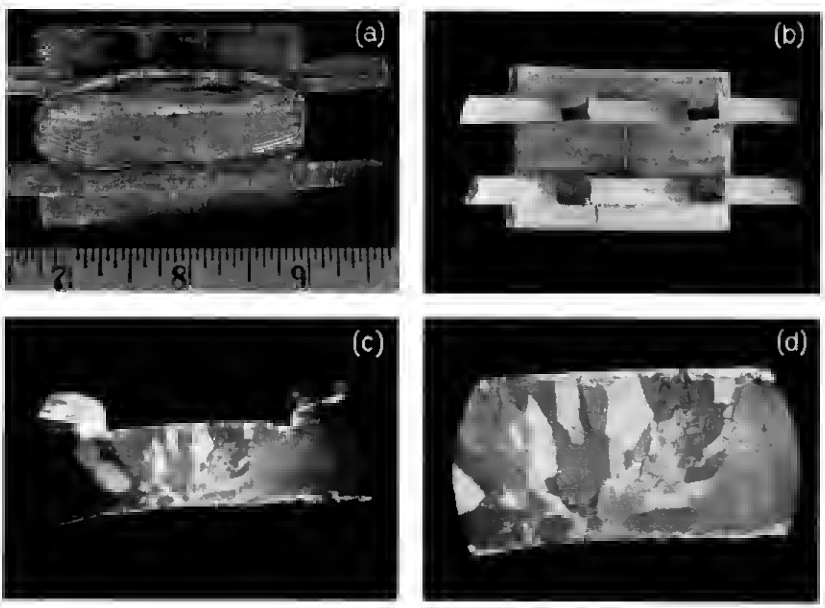


Fig. 7—(a and b) Front and back views of an early test bond; (c and d) 3× and 6× views of the bond area.

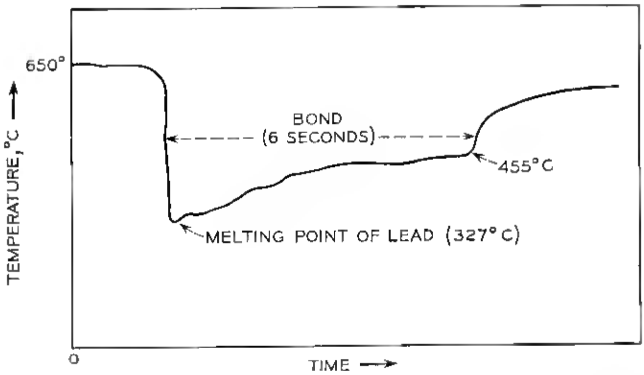


Fig. 8—Oscilloscope trace of ram surface temperature during typical bond.

lead will be heated only to a moderate temperature slightly above its melting point throughout the entire bonding cycle.

Tests verify that 900 to 1000 watts of electrical power are adequate to heat the MTP ram. The ram should be protected by suitable high-temperature thermal insulation to reduce thermal loss and to provide more rapid recovery of temperature between bonds.

The MTP heated ram lead-bonding process is practical for applications where it is possible to incorporate a simple back-up or confining fixture to contain the molten lead during bonding. It has been shown feasible to make excellent bonds with either:

(*i*) narrow back-up fixtures of metal,
(*ii*) resilient back-up fixtures of high-temperature plastic or foam such as used for the battery separators or insulators, or
(*iii*) thin high-temperature glass or plastic, adhesive-coated tape.

Back-up fixture types *ii* and *iii* can be left in the battery or can be removed after the bonding is completed. Metal back-up fixtures naturally have to be removed after the bond is completed.

This heated ram process uses simple, low-cost equipment; is capable of forming many bonds simultaneously; and is easy to control and reliable. However, it is clearly best suited for use where free access to the work parts is more readily available. For that reason, it is currently under consideration for use in bonding the lead strap to the periphery of the positive battery plates to create an electrical connection for the subsequent forming process for the lead paste.

V. CONTINUOUS MTP FUSION BONDING PROCESS

5.1 *Principles*

Figure 9 is an artist's rendition of the MTP continuous fusion bonding process. No back-up mold is required. In the heated ram process, the bond is made with the battery axis horizontal and the two lugs to be bonded located at the *top center* of the battery. In the continuous bonding process the battery axis is still horizontal but the lugs are bonded at the *bottom center* of the battery. In this way, gravity helps contain the molten lead on the *inside* (top) of the two lugs being bonded. The molten lead on the outside (bottom) of the two lugs being bonded is now directly contained by the bonding fixture itself. As a consequence, only the heated bonding tip need project within the confines of the circumference of the battery. This markedly simplifies the fixturing and stacking arrangements for the numerous battery plates, separators, and insulators required for each battery cell.

The battery is bonded from the bottom with a carefully shaped heated tip that projects up through a supporting plane. The plane is preferably curved to match the outside contour of the battery lugs. The battery lugs and the tip are moved relative to one another so that the tip progressively is passed along the entire length of the two lugs to be bonded. The lugs melt in the immediate hot-tip area only and quickly solidify as the tip passes by. The molten lead is contained automatically by the supporting plane on the bottom and by the non-molten portions of the lead parts adjacent to the bond area. Typically a time of from 15 to 25 seconds is required to bond two battery lugs using present equipment.

5.2 *Mechanical Design*

To describe the mechanical design of the tip unit, it is convenient to consider first the tip itself, then the tip assembly and the drive mechanism. A view of the tip is given in Fig. 10. The size of the projecting, active portion of the tip is approximately 0.125 inch by 0.2 inch in diameter. The tip is designed to project approximately two-thirds of the way through the parts to be bonded. If the tip projects all the way through the lead parts, there is a tendency to slow down the flow of the molten lead into the cavity left by the tip as it passes by.

The general requirements for an alloy to be used for the tip are that it should be:

(*i*) resistant to high-temperature corrosion,
(*ii*) resistant to molten lead,

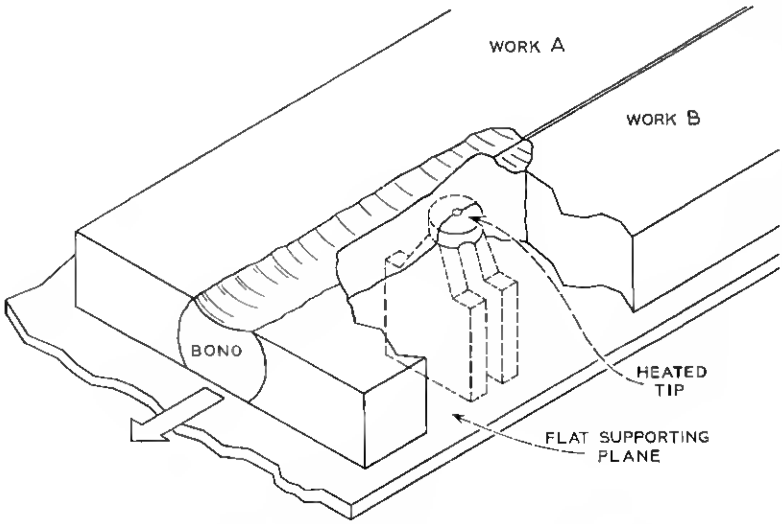


Fig. 9—MTP continuous-fusion bonding process.

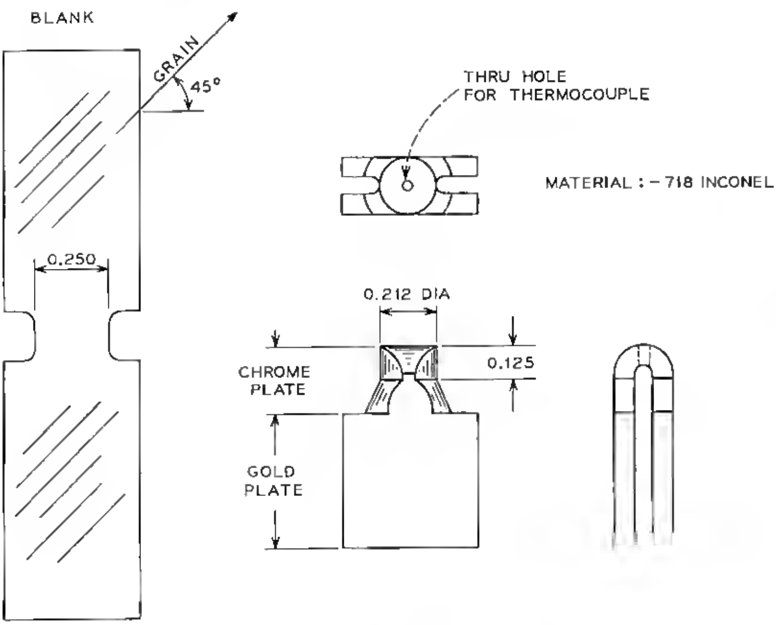


Fig. 10—Details of the heated tip.

(*iii*) formable at room temperature,
(*iv*) machinable with standard tools, and
(*v*) low in cost.

Also it sbould possess:

(*i*) bigb compressive strengths at high temperatures, and
(*ii*) bigb electrical resistivity.

Several high-temperature resistant metal alloys were tested for the heater tip, including Kantbal and Nichrome. The most success in bonding experiments, however, was achieved with Inconel 718 alloy shown in Table II. The tips are stamped out of a flat sbeet, thereby reducing their cost to a minimum. Tbe tips can be bent into the final shape at room temperature if the tip is oriented approximately 45° to the rolling direction of the flat sheet. For maximum tip life, the tip temperature during bonding should be kept to as low a value as possible. The reason is that tbe relationship of tip life versus temperature is exponential. To increase tip life further, the tips are plated with 0.5 to 1 mil of chromium on the active area.

Tbe temperature in tbe center of the active tip area is continuously sensed with a conventional thermocouple and displayed for the operator. In our laboratory test, we used 20-mil diameter cbromel-alumel thermocouple wire, glass-insulated, for these measurements.

Figure 11 shows a section view of the mounting assembly. This represents tbe heart of the bonding process. First, it provides a reliable connection of low electrical resistance between the power supply welding cables and tbe beated tip. Tbe electrical resistance of tbis connection is stable in spite of appreciable temperature excursions and the resultant mecbanical stresses. Secondly, the assembly design is modular in concept, allowing for the mounting of a complete assembly within the center-to-center

TABLE II—INCONEL 718 ALLOY, LIMITING CHEMICAL COMPOSITION IN PERCENT[a]

Nickel (plus Cobalt)	50.00–55.00	Cobalt	1.00 max.
Chromium	17.00–21.00	Carbon	0.08 max.
Iron	Bal.	Manganese	0.35 max.
Columbium		Silicon	0.35 max.
(plus Tantalum)	4.75–5.50	Phosphorus	0.015 max.
Molybdenum	2.80–3.30	Sulfur	0.015 max.
Titanium	0.65–1.15	Boron	0.006 max.
Aluminum	0.20–0.80	Copper	0.30 max.

[a] Conforms to AMS specifications.

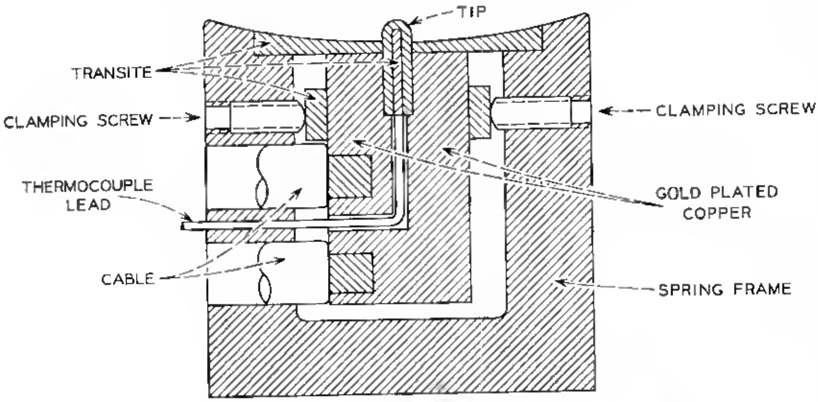


Fig. 11—Section view of the heated tip mounting assembly.

distance of adjacent bonds. Its attachment to the overall bonding machine is simple, allowing rapid and easy replacement.

The stable electrical resistance is achieved by using a compliant outer metal frame to compensate for the relatively large dimensional changes created by the temperature excursions. The frame is designed in the form of a U-shaped spring. The relatively large gold-plated copper blocks are brazed with a silver alloy to the stranded welding cable and are used to make electrical connection to the heated tip. The tip has a close-fitting, thin sheet of high-temperature transite insulation placed in its center around the previously inserted thermocouple wires. The two 0.5-inch square terminal ends of the tip are gold plated to assure minimum electrical interface resistance. The gold-plated copper electrodes are then pressed against the two contact faces of the tip by means of insulated screws inserted in opposite faces of the U-shaped spring frame. The spring frame is designed to flex during operation, thus maintaining a heavy clamping force between the copper electrodes and the heated tip at all times.

The force required to push the tip through the lead has been measured. When the support for the tip does not touch the lead, this force is typically less than ten pounds. When the support for the tip bears relatively firmly against the outside of the lead lugs, however, the force can approach an upper limit of approximately 100 pounds. Depending, then, on the degree of precision of the alignment between the tip support structure and the circumference of the battery lugs, the force required to push the tip through the lugs can vary between 10 and 100 pounds during one bond. Since the bonding speed should be controlled accurately,

this necessitates a motor-drive system that can withstand this variation with minimal change in speed. A constant-speed motor with a large gear reduction ratio worked quite well. The majority of tests were made with motor speeds yielding either 15 to 18 seconds or 26 to 30 seconds per bond.

We have made successful bonds using both (*i*) preset and fixed tip alignment and, (*ii*) spring-loaded, self-compensating tip alignment. The majority of tests were made with the preset tip alignment, since it simplified the mechanical design. Fixed alignment does, however, require that the shape of the battery plates be accurately controlled. Tests have confirmed that either a compensating or spring-loaded type of tip support structure can be used. The choice between a fixed or compensating design depends largely upon the precision to be expected in the manufacture of the battery plates.

5.3 *Electrical Design*

During the course of the experimental work, it became apparent that it would be advantageous to have two power supplies, one for current to heat the tip and one to supply current flowing through the lead. To understand why, consider the sketches of Fig. 12, showing the heated tip under three conditions. In each of the three sketches, the four points of interest in the following discussion are identified as A, B, C and D. In the idle condition occurring between bonds (left), the tip can readily be heated to a uniform temperature as shown. With just one power supply to heat the tip, no current flows in the lead, and it can be seen in the center sketch that the points of physical contact (B and C) between the heated tip and the work parts have dropped

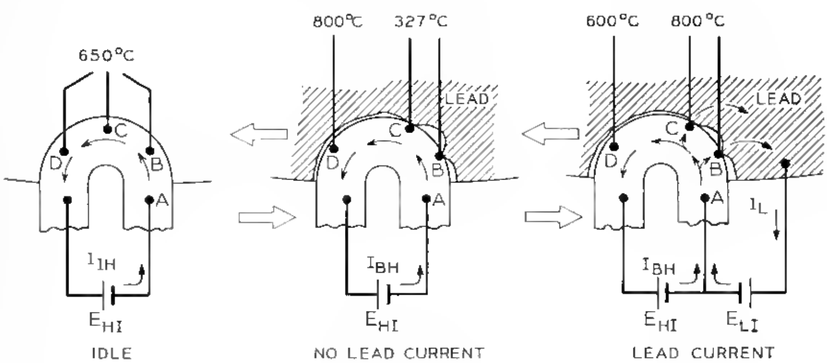


Fig. 12—Heater tip temperature profiles.

to a much lower temperature than the balance of the heated tip. This occurs rapidly and is, of course, exactly the reverse of what is desired. The right-hand sketch of Fig. 12 illustrates what happens when "lead current" is applied by means of a second power supply. This additional current through the tip to the lead lugs serves the useful function of heating the points of contact between the heated tip and the work to a higher temperature than the balance of the tip. This is precisely what is needed. It is interesting to note that as the points of contact (usually two or more) between the heated tip and the lead lugs change in location, the old points of contact that were disrupted automatically cool down and the new points of contact automatically heat up.

Figure 13 is a schematic diagram of the original laboratory power supply for the MTP continuous fusion bonder. The area of most interest

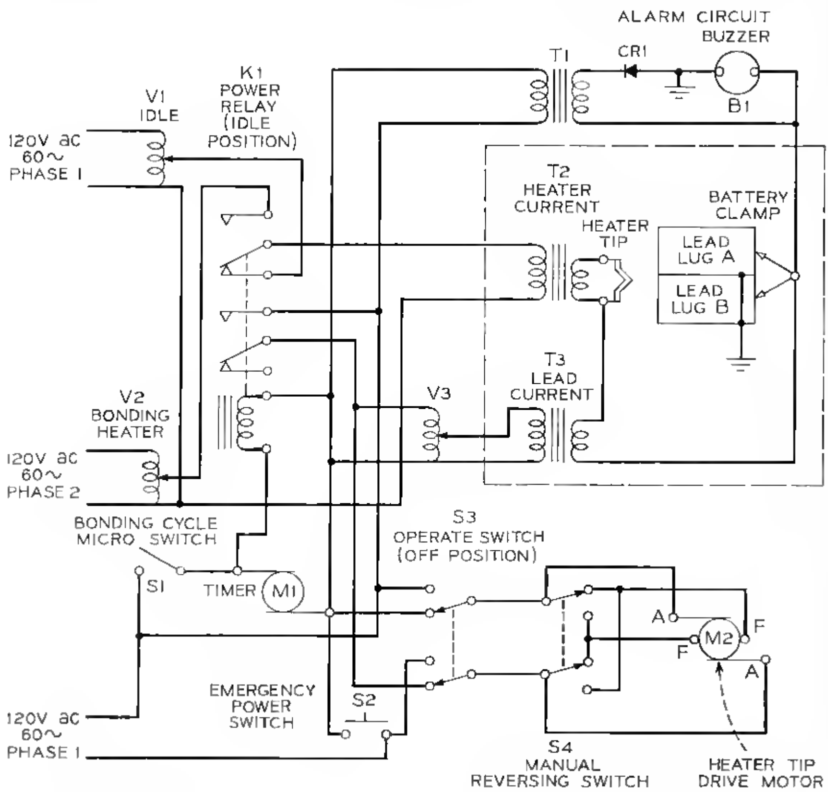


Fig. 13—Schematic diagram of laboratory power supply for MTP continuous-fusion bonder.

is identified by the dashed line. Two step-down transformers, T-2 and T-3, are used to provide the relatively large bonding currents. Both power transformers are, in turn, fed by autotransformers to provide a convenient means of changing bonding currents. Transformer T-2 provides the current for heating the hot tip directly and hence is called the heater-current power supply. Transformer T-3 passes current through the heated tip and thence to the lead hattery lugs to he honded. This second power supply is called the lead-current power supply. As discussed above, the function of this current is to heat the tip hotter in the areas of contact between the tip and the lead battery lugs. The passage of this electrical current through the tip to the lead work parts creates only minimal heating of the lead itself due to the relatively high electrical resistance of the heated tip compared to that of the lead.

It is necessary to provide electrical connection from the lead current power supply to the hattery lead lugs. Separate lead current clamps and cahles are used for each hond when simultaneous multiple honds are being made. In this manner the power supply for each heater tip is isolated except for one common point, thus preventing interaction hetween the different power supplies. Either a simple alarm circuit (step-down transformer T-1 in Figure 13) should he provided to assure that connection to the lead current power supply has heen made, or as an alternative, the lead clamp should he locked in position automatically as the heater tip is raised into position ready for bonding.

Since the two power supplies have a common resistance consisting of a portion of the heater tip and a predetermined portion of the total length of the supply cable*, the current flowing in one circuit does affect the current flowing in the other. This coupling can he adjusted to be either aiding or cancelling. Negative coupling is preferred, since this provides maximum heater current for the tip when the lead current is not flowing, and decreases the heater current when the lead current is flowing. In Fig. 12 I_{IH} is the idle heater current, I_{BH} is the bonding heater current, and I_L is the lead current. Note in Fig. 12 that the two ac power supplies are shown as dc hatteries. When they are connected to provide negative coupling (that is, with the polarities shown), then the common-current path in the heater tip is limited to the region from points A to C, with most of the current concentrated between points A and B. It can he seen from the center and right-hand views that adding current I_L will reduce the magnitude of current I_{BH} while simultaneously increasing the current flow in regions surrounding points B and C.

* Approximately 5 inches in our test using #4 AWG cables approximately 43 inches in length.

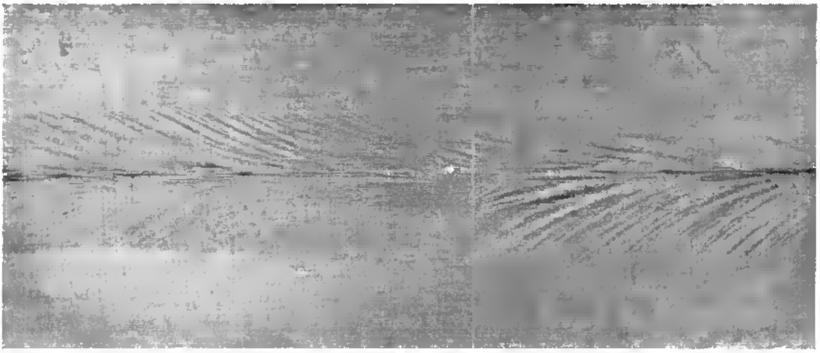


Fig. 14—Top surface of two bonded flat-lead strips.

This increased current generates additional heat energy by joule heating at points B and C. The thermal energy is then transferred to the lead by thermal conduction to create uniform, void-free bonds.

Early experiments using a heated tip of similar design, with the thermocouple mounted in the center of the tip and coupled to a high-speed potentiometric controller, afforded convincing evidence that conventional feedback temperature control did not adequately satisfy this application. For example, if the thermocouple area of the tip was not contacting the lead, the controller would sense a high temperature and would not feed additional power to the tip, even though the actual points of contact between the tip and the lead could be below the melting point of lead. The resultant errors were many hundreds of degrees centigrade and occasionally caused burn-out of the tip.

In summary, two power supplies connected for negative coupling are used to provide the equivalent of a multi-point automatic temperature control system which adequately compensates for random changing points of contact between the tip and the lead work part with minimal electronic circuitry. The idle heater current (see Fig. 13) functions to keep the bonding tip at a moderate temperature between bonds. It can be eliminated if the tip is allowed to cool back to room temperature between bonds and then pulse-heated to bonding temperature just prior to contacting the lugs.

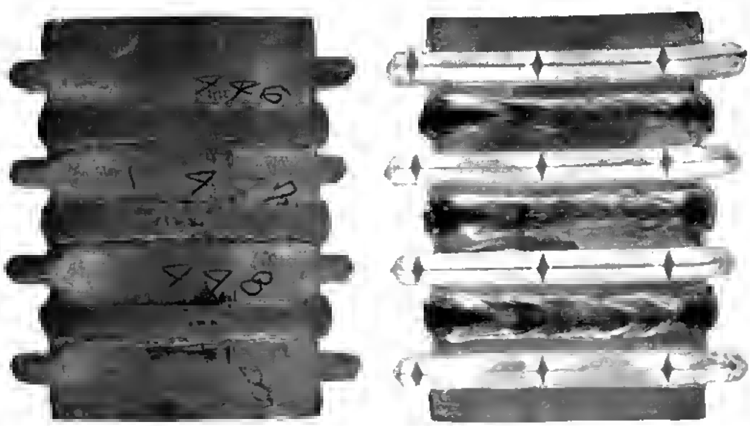
In our initial test, 60-cycle 120 V ac power was used. Two circuits are required having a 120° phase relationship. This is necessary because if both the lead current and the heater current are in phase, the heating rate of the tip is so rapid (typically 500°C/second) that there would be appreciable temperature swings between successive half cycles of

current. The improvement in tip temperature control and life is pronounced when a deliberate out-of-phase condition between the heater current and lead current power supplies is provided.

5.4 *Performance of the Experimental Bonder*

Figure 14 shows the top surface of two flat lead strips, having the same thickness as the battery lugs, that were bonded with this bonding process. Lead oxide was left in place on the lead parts prior to and during bonding. Both lead strips rapidly melted in the center, flowing together while the lead oxide floated to the top as shown. Many test bonds have been made with relatively heavy layers of lead oxide present in the bond area. Reasonable amounts of lead oxide can be floated out in the molten stage to provide good bonds. For manufacture, however, the forming process for the positive plates provides an excessively heavy layer of dark oxide, and it is not deemed practical to attempt to bond through this layer of oxide, since its depth and character are not specified or controlled. Hence, a mechanical or chemical pre-cleaning of the bond area is recommended. Preferably this pre-cleaning should be done as close as possible to the time the bond is to be formed. This is not unduly critical, however, since good bonds can readily be made to plates that have been pre-cleaned several days prior to bonding.

Figure 15 shows front and back views of three typical bonds. These



FRONT BACK

Fig. 15—Photographs of three bonded lugs.

lugs were cut out of complete hattery plates for the purpose of the photographs.

The start and end of the honds were not prohlems using a constant-speed tip drive with flat lugs. With curved lugs the hattery plates are kept stationary and the tip assemhly is moved from one end of the lugs to the other. Thus gravity tends to cause the molten lead to fall hack into place at hoth the beginning and end of honding. This has proved to he quite helpful. The tip is advanced at a constant speed prior to, during, and after honding. In some cases the additional sophistication of a variahle speed, programmed, motor-driven system might he worth considering.

The left- and right-hand sketches in Fig. 16 show a slight projection at the start and end of the hond. The shape of the lugs prior to bonding is shown hy the dashed lines. Note the small raised pool of molten metal directly ahove the leading edge of the tip as it progresses through the bond. As the tip emerges from the hond, a very small quantity of lead, typically one-half the volume of the exposed tip, is pulled out of the hond hy the advancing tip. These slight distortions of hond shape are prohahly minor enough to he ignored. Such distortions can be equalized, however, hy tilting the lugs off center so that the leading edge of the lug is slightly higher than the trailing edge.

Figure 17 shows two metallurgical views of sections of honds. These samples were not etched hut were very carefully polished to minimize smearing. Figure 17a shows a view of a typical hond made under the following conditions:

(*i*) 280 amps RMS lead current,
(*ii*) 295 amps RMS heater current,
(*iii*) 830°C honding temperature,
(*iv*) 480°C idle, and
(*v*) 28 seconds honding time.

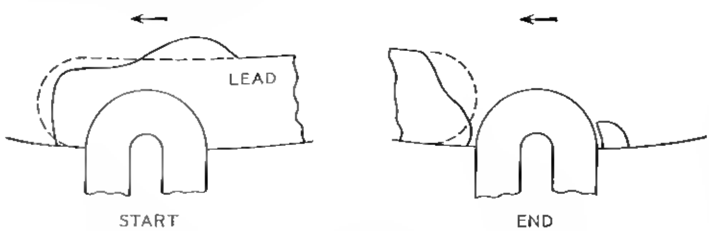


Fig. 16—Bond shape at the beginning and end of a lug.

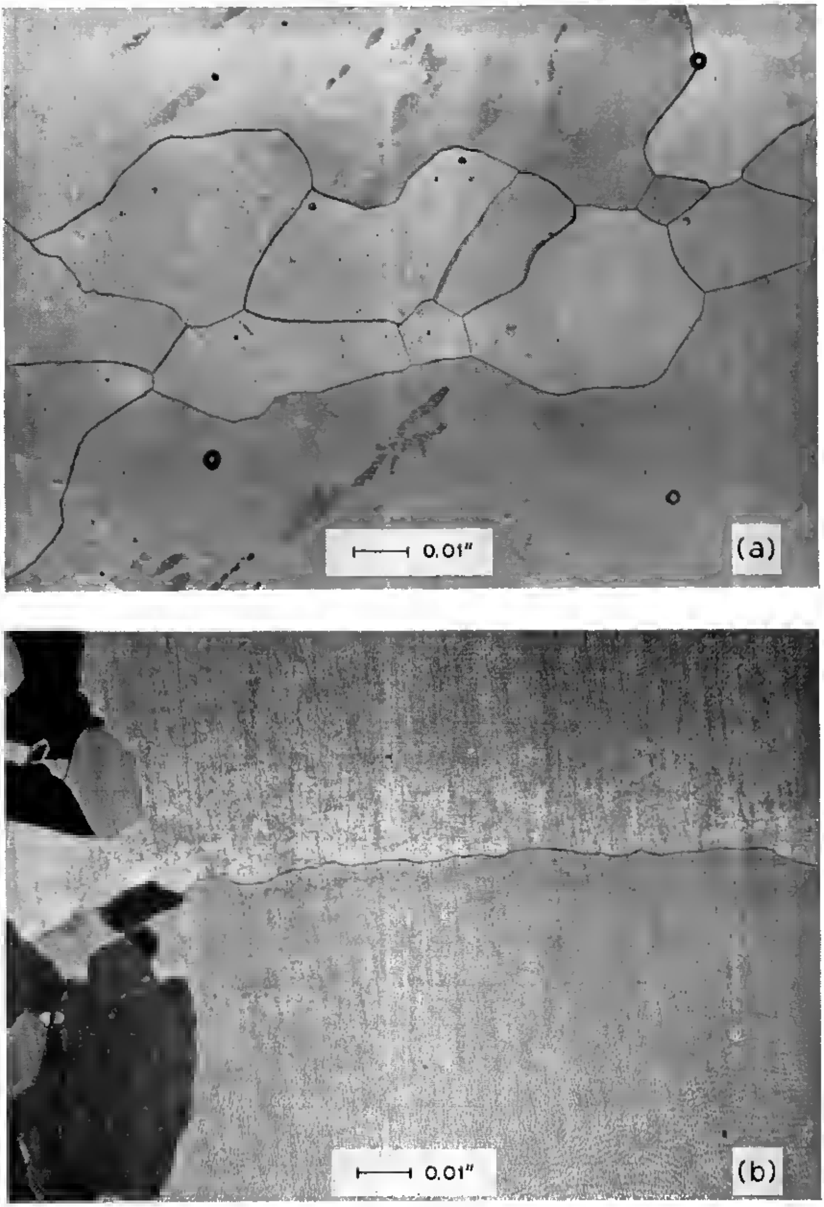


Fig. 17—Metallurgical views of typical bonds. (0.4″ actual = 0.01″).

Figure 17b shows a view of a pair of lugs that were bonded three times. These three bonds were made under the following conditions:

(*i*) 245 amps RMS lead current,
(*ii*) 260 amps RMS heater current,
(*iii*) 1030°C bonding temperature,
(*iv*) 720°C idle, and
(*v*) 17 seconds bonding time.

The repeated bonding of the same set of lugs clearly confirms that these bonds can be readily repaired. Also, such metallurgical views indicate that homogeneous, clean bonds are formed.

It requires approximately 6000 joules of energy to form an MTP continuous fusion bond to one pair of lugs 0.188 inch thick by approximately 2.25 inches long.

Two test cells of three and four positive battery plates witb appropriate separators and insulators with all the bonds made by the MTP continuous fusion process were submitted to accelerated life tests at Bell Telephone Laboratories, Murray Hill, N. J. In addition, two test cells bonded by the MTP heated ram process underwent accelerated life tests. All four of tbese first test cells withstood the equivalent of several centuries of normal operation without weld failure.

Analyses of bonded samples were also made to determine if there were traces of nickel or chromium, the major metals involved in tbe tip. Tests carried out by L. D. Babusci of Bell Telephone Laboratories indicate only trace amounts (below 0.001 percent) of these materials in the bonds.

Figure 18 shows an oscilloscope trace of the temperature sensed at the center of the tip during a typical bonding cycle. There is an ap-

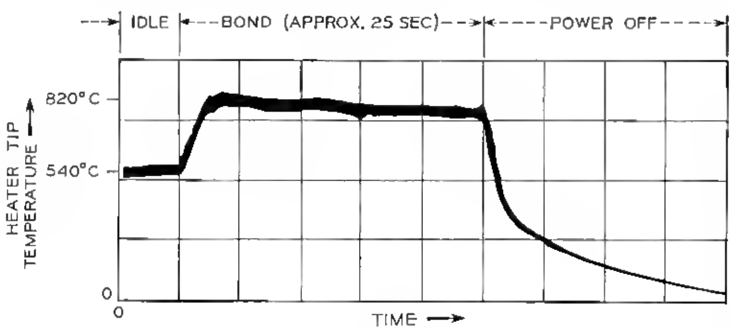


Fig. 18—Oscilloscope trace of tip temperature during typical bond.

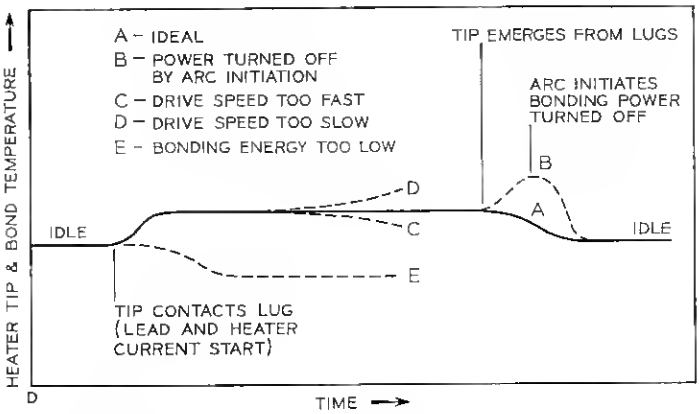


Fig. 19—Variations in tip and bond temperature caused by different power settings and bonding speeds.

preciable temperature differential between the tip and tbe lead. Consequently, this temperature represents the probable upper limit for the temperature of the lead during the bond. It should, therefore, serve as a convenient dynamic indication of bond quality since it is sensitive to variations in both the bonding equipment and tbe lead lugs tbemselves. The temperature during bonding can be displayed on an oscilloscope or a strip chart recorder, or it can be incorporated in a comparison circuit yielding simple "go-no go" type control.

Next, the effects of the different process controls on bond formation is discussed. Tests have indicated that wben the idle tip temperature is varied, the variation primarily affects tbe *beginning* of tbe bond. Changing the heater current, bowever, primarily affects the outside or *bottom* of the bond. Changing tbe lead current, in turn, primarily affects the inside or *top* of the bond. And finally, varying the speed of the bond tends to control the *end* of the bond. Consequently, independent control can be exercised over eacb of the four surfaces of tbe bond.

Figure 19 depicts the variations in tip and bond temperature caused by different power settings and bonding speeds. Curve A represents the optimum. It sbows a gradual rise from tbe idle temperature to bonding temperature, with a stable plateau througbout bonding followed by a gradual drop-off at the end of tbe bond. Curve B confirms the sharp rise in temperature at tbe end of the bond that results if current is maintained as the tip emerges from the back end of tbe lug. Curve C shows that if the drive speed is too fast, bonding temperature will start to droop, causing tbe back end of the bond to become too cold. Con-

versely, Curve D shows the reverse situation when the drive speed is too slow. Finally, Curve E shows the situation when the heater current and lead current settings provide too little power, thus allowing the bonding temperature to drop too low in value.

5.5 *Operation*

The operation sequence is as follows for either individual or multiple bonds:

(*i*) Each heater tip is adjusted to the desired idle temperature.

(*ii*) The operate switch (S3 of Fig. 13) is depressed and held depressed throughout the entire bonding process. Once this button is released, the motor is stopped and tip temperatures automatically drop back to the idle position as a "fail safe" mode of operation.

(*iii*) The motor is started, advancing the tip. Once the leading edge of the tip touches the lead lugs, the voltage across each heater tip is switched from the "idle" setting to the higher "bonding" setting by the microswitch S1.

(*iv*) As the center of the tip lines up with the trailing end of the lug, both the heater and lead currents are turned off by the microswitch S1, switching back to the idle tip heater supply. The motor continues to operate until the tip has advanced at least 0.25 inch past the back end of the lug.

(*v*) The bonds are complete at this point. To prepare for the next set of bonds, the tip is lowered out of contact with the lugs and is retraced to its starting position. The tip is brushed lightly with a brass bristle brush to remove any lead particles adhering to the tip after each bond. It is then either slid over axially until it is in line for the next adjacent lug, or the battery assembly fixture is rotated an appropriate number of degrees to line up the next row of lugs.

Table III lists typical currents, voltages and temperatures measured at appropriate points in the control circuit for two speed settings. It should be noted that the design of the heater tip influences these values. The listed parameters represent the approximate rms values of voltages and currents as measured or calculated, using the laboratory prototype curved lug bonding fixture with 120 volts ac input to the autotransformers. The two power supplies were connected to provide negative coupling with a 120° phase difference.

In the first prototype bonders, a microswitch was used to turn the heater and lead current voltages on and off for all tips at the beginning and end of each bond. An alternative technique that appears to offer

TABLE III—TYPICAL BONDING PARAMETERS

		Idle		During Bond	
		15–17 Sec. Bonding Time	28–30 Sec. Bonding Time	15–17 Sec. Bonding Time	28–30 Sec. Bonding Time
Heater current power supply					
Step down transformer, T2	Secondary current	165A	130A	315A	290A
	Secondary voltage (Open circuit)	1.2V	0.9V	2.2V	2.0V
Lead current power supply					
Step down transformer, T3	Secondary current	0	0	330A	280A
	Secondary voltage (Open circuit)	0	0	2.3V	2.0V
Bonding temperature	At center of heater tip	760°C	540°C	930°C	820°C

more promise for production applications is individual sensing of the beginning of each lug for each pair of lugs being bonded. This can be done by turning on the lead current before the tip first contacts the lugs. Then, when the tip contacts the lug, the initiation of lead current is sensed with an appropriate transformer, using one lead current cable as a single turn primary. The output of the transformer is used directly to power a relay whicb turns on the heater current power supply. Standard power relays carry out this function within 25 milliseconds. At a total bonding time of 25 seconds, this represents a tip travel of 0.025 inch and yields higher precision than when microswitches are used.

Turning off the power after the bond is completed is slightly more complex. First, turn-off should be independent of motor speed so as to provide a reasonable tolerance for variations in motor speed under changing load. Second, turn-off should ideally occur at the point when the hot tip has emerged approximately one-half way out from the back end of the lug. The reason is that the tip, as it emerges from the lug, pulls a narrow strand of molten lead with it. Consequently, the path of the lead current from the tip back to the lugs increases in resistance and applies an excessively large quantity of thermal energy to the back end of the bond. This is further aggravated as the tip continues to move, rupturing the now thin strand of molten lead and creating an arc which adds still additional thermal energy.

The optimum metbod is to turn off both the lead current and beater current upon sensing a predetermined distance of tip travel after initiation of lead current. This can be done with stepper motors or stepper relays, one for each tip, fed by a single electromechanical pulse generating switch operated hy the tip drive sbaft. All the units would he reset automatically at the end of eacb bonding cycle. This tecbnique has tbe advantage that the individual positive plates can he stacked together with less precise alignment without affecting the quality of the hond. In addition, the operator bas the freedom of changing the honding speed without having to readjust the on-and-off mechanisms.

The MTP continuous fusion bonding process can form successful honds between lugs wbicb are quite severely out of alignment. However, tip temperatures rise above the normal level, reducing tip life. Figure 20 shows three of the most common types of misalignment errors. Sucb errors usually occur to some degree because of the distortion in shape that results from handling and stacking large numhers of soft, pure-lead plates. However, successful honds have heen made wben lugs are radially or tangentially out of alignment by as much as 0.125 incb. This is quite severe when one considers that the lugs are only 0.188 incb thick. This capability for handling misalignment is a significant production advantage.

Figure 21 is a photograpb of the second prototype machine huilt by Western Electric at Kearny, N. J., utilizing the ahove design principles. This machine, shown installed at the Design Capability Line, was used to confirm that two bonds could he made simultaneously and also to test out tbe various control techniques. An improved version of this machine with the capability of bonding up to ten pairs of lugs simultaneously is nearing completion.

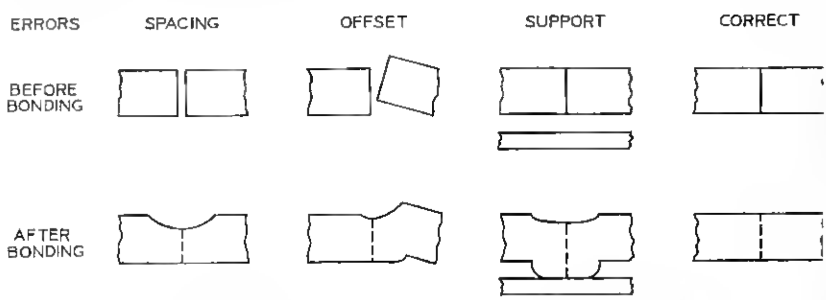


Fig. 20—Misalignment errors and resultant bond shapes.

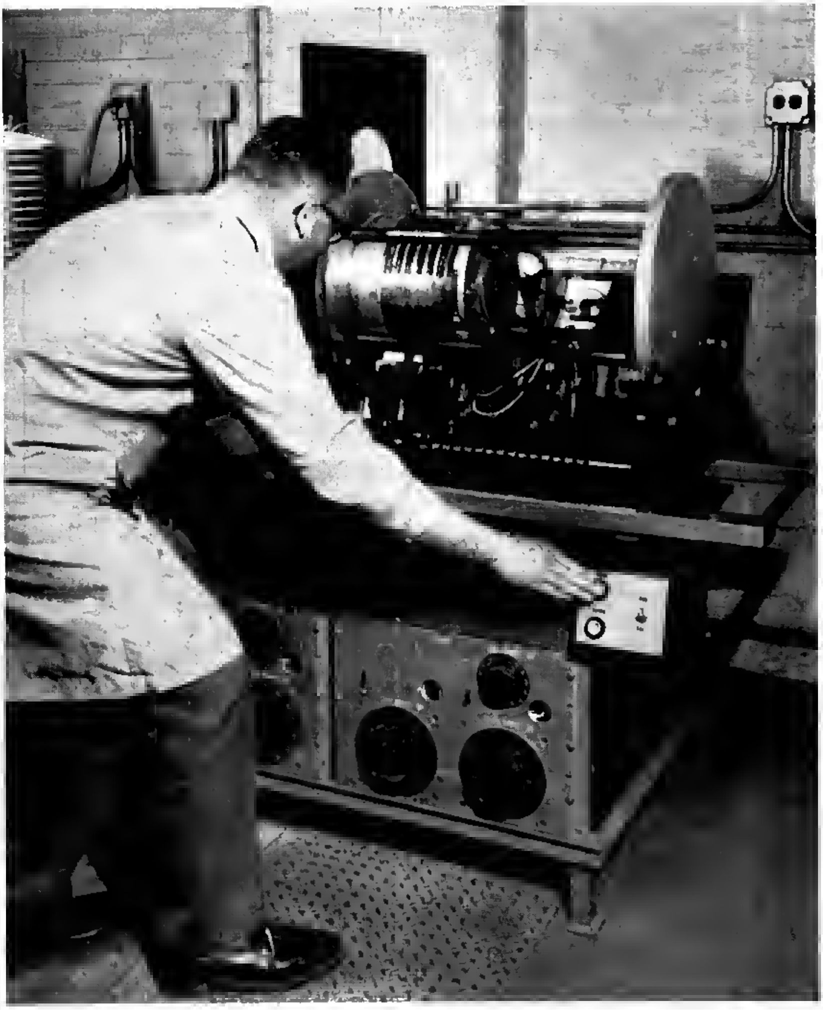


Fig. 21—Prototype MTP continuous-fusion bonder.

As production experience accrues with this new bonding process, an additional simplification will be considered. All bonding tips could be held stationary, while the battery assembly is rotated in a continuous, constant-speed motion for one complete revolution. This approach has already proven feasible.

VI. CONCLUSIONS

This article discussed the basic requirements for bonding the positive battery plate lugs of the new lead-acid battery. Two new bonding concepts were developed specifically to meet the requirements of this program. The MTP continuous-fusion bonding process was chosen for the positive plate bonding due to its many control advantages. These advantages include:

(*i*) simultaneous multiple bonds;
(*ii*) accurate and repeatable temperature control;
(*iii*) simple electronic controls;
(*iv*) individual control capability for the top, bottom, front or back end of the bond;
(*v*) elimination of any back-up or confining fixtures within the circumference of the battery;
(*vi*) automatic initiation and removal of bonding power for each pair of lugs being bonded;
(*vii*) capability of bonding through severe contamination;
(*viii*) capability of bonding severely misaligned lugs; and
(*ix*) rapid bonding speed.

The second bonding process, MTP heated ram fusion bonding, is currently being considered for a secondary application of bonding lead straps to the periphery of the positive battery plates for use in the paste forming process. Additional applications for these processes are currently being studied involving the transfer of up to 90,000 joules of energy per bond. The basic bonding concepts involved in both processes suggest the possible extension of MTP fusion bonding to other low melting temperature metals such as tin, zinc, aluminum, magnesium, and so on.

VII. ACKNOWLEDGMENTS

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